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Measuring Visual Opacity Using Digital Imaging Technology

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ABSTRACT

The U.S. Environmental Protection Agency (EPA) Reference Method 9 (Method 9) is the preferred enforcement approach for verifying facility compliance with federal visible opacity standards. Supporters of Method 9 have cited its flexibility and low cost as important technological and economic advantages of the methodology. The Digital Opacity Compliance System (DOCS), an innovative technology that employs digital imaging technology for quantifying visible opacity, has been proposed as a technically defensible and economically competitive alternative to Method 9. Results from the field application of the DOCS at EPA-approved Method 9 smoke schools located in Ogden, UT, Augusta, GA, and Columbus, OH, demonstrated that, under clear sky conditions, the DOCS consistently met the opacity error rate established under Method 9.

Application of hypothesis testing on the smoke school data set confirmed that the DOCS was equivalent to Method 9 under clear sky conditions. Under overcast sky conditions, human observers seemed to be more accurate than the DOCS in measuring opacity. However, within the smoke school environment, human observers routinely employ backgrounds other than sky (e.g., trees, telephone poles, billboards) to quantify opacity on overcast days. Under conditions that compel the use of sky as plume background (e.g., emission stacks having heights above the tree line), the DOCS appears to be a more accurate methodology for quantifying opacity than are human observers.

IMPLICATIONS

Since its promulgation, Method 9 has been the methodology adopted by both regulators and permitted facilities to validate compliance with federal visible opacity standards. Because it depends on the visual precision of human observers, Method 9 results are vulnerable to claims of bias, distortion, and outright fraud. The DOCS, which generates a permanent digital record of visual emissions, has been proposed as an alternative to Method 9. When sky is employed as background, the DOCS not only exhibits comparable performance flexibility to Method 9 but is also economically competitive and can quantify plume opacity with an accuracy that routinely exceeds the level established by Method 9.

INTRODUCTION

The presence of visible air emissions from industrial operations provides irrefutable evidence that airborne particles are being discharged into the atmosphere. Not only has the public expressed its concern regarding the negative psychological effects of visible emissions, but, under many circumstances, particulate emissions have been identified as the cause of increased human health and environmental risk.[1,2] Because of public concerns regarding the potential health and environmental impacts associated with visible air emissions, current federal statutes as well as many state and local air quality control laws

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currently regulate the opacity of plumes (i.e., point sources of air pollution) as well as fugitive particulate emissions. Opacity is defined as the percent of light attenuated by airborne emissions. In other words, an opacity value of 10% indicates that 10% of the incident light is absorbed, scattered, or otherwise blocked by the plume, while 90% is transmitted. The federal opacity standards for emissions from various industries are found in 40 CFR Part 60 (Standards of Performance for New and Modified Stationary Sources) and 40 CFR Parts 61 and 62 (Emission Standards for Hazardous Air Pollutants).[2]

The primary method for determining compliance with federal opacity standards is U.S. Environmental Protection Agency (EPA) Reference Method 9 (i.e., Method 9—Visual Determination of the Opacity of Emissions for Stationary Sources). Method 9 relies on the ability of trained human observers to visually estimate the opacity of a plume by taking a series of opacity measurements at the rate of one every 15 sec for a specified period of time (typically 6–60 min).[3,4] The collective set of opacity measurements then is averaged to develop a single opacity reading for the regulated source, which is subsequently compared against permitted levels. To qualify as an EPA Reference Method 9-certified human observer, an individual must attend and successfully complete an EPA-approved Reference Method 9 visual opacity smoke school once every 6 months. EPA certification requires that each candidate complete EPA Reference Method 9 classroom and field training and receive a passing grade on an opacity field test. To successfully pass the opacity field test, the candidate must demonstrate the ability to accurately assign an opacity value to each of 25 white and 25 black smoke plumes with an error rate not to exceed 7.5%.[5]

While Method 9 has an extensive history of successful employment, the costs associated with smoke school tuition fees, an attendee's travel and lodging, and the 3 days that employees are typically absent from their primary work assignment support the claim that maintaining active certification can be expensive. Beyond the financial burden associated with an individual maintaining EPA Reference Method 9 certification, reliance on human observers to estimate visible opacity suggests that the results are inherently susceptible to bias and other factors that could potentially affect their accuracy. Moreover, it is not uncommon for a facility's air compliance personnel and government regulators to arrive at significantly different results when applying Method 9 procedures to estimate the opacity of a permitted source.[6]

A major challenge in estimating visible opacity is the impact of particle concentration, particle size distribution, particle optical properties, solar illumination angle, and moisture content of the plume on the measurement.[4,5] To minimize the impact of these and other variables on the opacity determination, large industrial operations often install sophisticated optical instruments called transmissometers to provide continuous opacity monitoring. When properly installed and calibrated, transmissometers provide effective, real-time opacity measurements. However, the capital and maintenance costs associated with the installation and operation of these instruments can be prohibitive economically. Moreover, like all automated compliance-monitoring devices, these instruments require that a permitted source be equipped with a reliable alternative method for estimating opacity in case of instrument failure. EPA Reference Method 9 is most frequently the default alternative method for estimating opacity.

The current study was designed to evaluate the technical performance of the Digital Opacity Compliance System (DOCS), a technology that has been proposed as a potential cost-effective alternative to EPA Reference Method 9 for measuring opacity.[7] The DOCS uses a commercial off-the-shelf digital camera to capture images of visible opacity, which are then downloaded to a standard personal computer and analyzed using computer software. The DOCS has not only been advertised as an accurate and reliable alternative technology for quantifying opacity but has the added advantage of furnishing the user with a permanent visual record of the emissions.

BACKGROUND

Theory

In the DOCS, digital photographs of visible emissions are taken from valid positions according to EPA Reference Method 9 specifications.[7] Once downloaded to a computer on which the DOCS computer software has been installed, the digital images can be evaluated for opacity. The initial steps in analyzing the digital image for opacity include (1) activating the DOCS opacity computer program, (2) retrieving those digital photographs that are to be evaluated, and (3) using the computer program to draw an analysis box (or grid) around that portion of the visible emissions that will be analyzed (Figure 1).

After selection of the analysis box, the DOCS software must distinguish that part of the digital image that corresponds to the visible emissions from that which corresponds to background (i.e., sky conditions). By assuming the pixels located at the outside of the analysis box correspond to background and those located in the center represent visible emissions, the software is able to determine whether the emissions are lighter or darker than background.

The DOCS software basically begins calculation of the plume opacity scale by assigning 0% opacity to those pixels within the image whose maximum saturation value

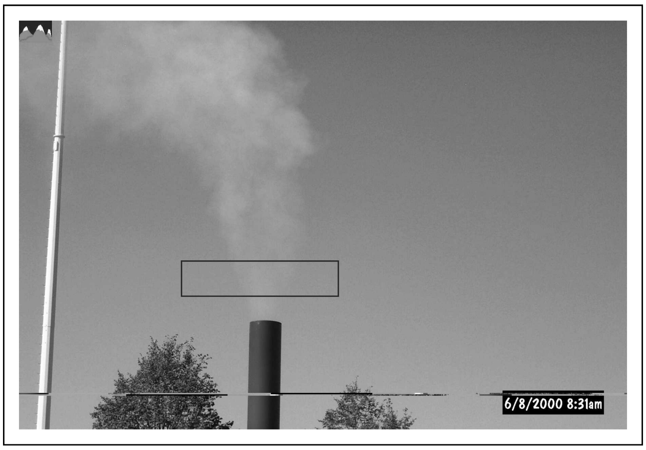

Figure 1. The analysis box drawn around the visible emissions.

is found to equal the saturation value of the background color. Through statistical regression, the software then establishes an opacity scale that represents the saturation values of each pixel. By projecting the saturation values of each pixel onto the opacity scale, the software estimates the opacity of every pixel, which is combined to yield plume opacity.

Practice

Under normal circumstances, the user of the DOCS software rarely needs to understand the complex mathematical relationships associated with digital image transformation. Rather, the software user simply draws an analysis box around the area of the plume to be analyzed for opacity. The DOCS computer software then selects the purity of color (i.e., saturation) that best corresponds to the background based on the spectral information contained in the pixels located at the edge of the analysis box. The size and shape of the analysis box, which is controlled by the user of the software, must be chosen judiciously because the final opacity measurement ultimately will depend on what part of the image the DOCS software identifies as background.

An important feature available within the DOCS software package is the brush function, which essentially allows the photograph analyzer the option of electronically selecting any segment of the digital image as background. The analyzer then brushes the selected background on both sides of the plume. The DOCS computer algorithm then compares the contrast between the plume and the selected background to generate an opacity reading.

METHODOLOGY

In developing the scope of the field study, it was recognized that the ability of the DOCS to estimate plume opacity accurately could vary significantly depending on climatic conditions. In other words, temperature, humidity, and other environmental factors could potentially affect the accuracy of the DOCS. To estimate the extent to which environmental conditions influenced the ability of the DOCS to measure accurately plume opacity, the DOCS was evaluated at geographical locations representing a range of climatic conditions, which included EPA-approved Reference Method 9 smoke schools conducted in the states of Utah, Georgia, and Ohio.

Field Activities

During the field study, four commercially available digital cameras (e.g., Kodak DC290 or Kodak DC265) were employed to photograph visible emissions generated as part of the EPA Reference Method 9 certification smoke school. The DOCS photographic imaging software was installed and tested on each of the cameras before any photographs were taken. Use of the DOCS camera software is a security requirement that essentially guarantees that the digital photograph cannot be altered before an opacity determination. No technical adjustments or physical modifications of the cameras were necessary to operate the DOCS photographic imaging software.

Each camera was positioned on a tripod to provide a clear view of the visible emissions. The minimum distance of the cameras from the stack was equivalent to at least three stack heights with the sun oriented in the 140° sector to the back of the camera/observer (Figure 2). These field procedures were adopted to be consistent with the published requirements for valid EPA Reference Method 9 visible emissions opacity measurements.[5]

Two cameras were placed directly in line between the sun and the smoke stack while each of the two remaining cameras was placed at the maximum allowable azimuth angle (see Figure 2). In addition to the four digital

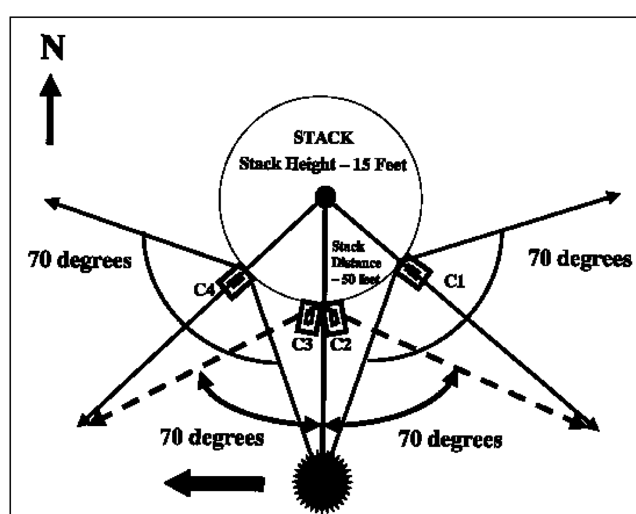

Figure 2. Positioning of the DOCS cameras (C1, C2, C3, and C4) and visual observers during the field study.

cameras used during the DOCS evaluation, an EPA Method 9-certified smoke reader (i.e., human observer) was assigned to each camera location to read plume opacities during the first day of the DOCS testing. The objective of assigning a limited number of EPA Reference Method 9-certified human observers to measure plume opacity during field testing was to establish a comparison between the relative accuracy of certified human observers and the DOCS. Unlike the EPA Reference Method 9 certification field-testing procedures, the EPA Reference Method 9-certified human observers were not provided an opportunity to calibrate their vision before estimating plume opacity. The EPA-certified smoke generator that was used during the subsequent EPA Reference Method 9 certification field test initially was employed in the 1-day certified human observer/DOCS side-by-side evaluation. EPA Reference Method 9-certified human observers who were scheduled to participate in the 1-day technology comparison had active EPA Reference Method 9 certifications at the beginning of the fieldwork.

Weather Monitoring

During the EPA-approved smoke school DOCS evaluation, on-site field personnel recorded the values of specific climatic parameters including (1) mean air temperature, (2) average wind speed, (3) maximum wind speed, (4) wind direction, (5) sky conditions, (6) relative humidity, (7) visibility, (8) barometric pressure, (9) precipitation, (10) horizontal sun angle, and (11) vertical sun angle during each day of testing. Methods used to estimate the value of each climatic parameter are summarized in Table 1.

Table 1. Methods used to estimate the value of various climatic parameters.

Parameter	Method
Mean temperature	Standard liquid thermometer (Eastern Technical Associates, Inc.)
Average wind speed	Standard anemometer (Eastern Technical Associates, Inc.)
Max wind speed	National Weather Service (National Oceanic and Atmospheric Administration—www.nws.noaa.gov)
Wind direction	Standard anemometer (Eastern Technical Associates, Inc.)
Sky conditions	Visual observation
Relative humidity	Sling psychrometer (Eastern Technical Associates, Inc.)
Visibility	National Weather Service (National Oceanic and Atmospheric Administration—www.nws.noaa.gov)
Barometric pressure	National Weather Service (National Oceanic and Atmospheric Administration—www.nws.noaa.gov)
Precipitation	National Weather Service (National Oceanic and Atmospheric Administration—www.nws.noaa.gov)
Horizontal sun angle	Magnetic compass (Eastern Technical Associates, Inc.)
Vertical sun angle	Abney level (Eastern Technical Associates, Inc.)

Opacity Determination Using the DOCS

After collecting the digital photographs of each plume, opacity was estimated using the DOCS computer software by an eight-member panel consisting of federal government civilian personnel, U.S. military personnel, and federal government contractors. Each panel member was provided a compact disc that contained all of the digital photographs taken from the respective smoke school as well as the DOCS computer software and user guide. The panel members were required to work independently to estimate the plume opacity of each digital photograph using the furnished computer software. Once panel members had completed their analyses, the opacity results were transferred and stored electronically in a relational database for subsequent statistical evaluation. An independent quality control officer was assigned the responsibility of maintaining the integrity of all opacity data, including the opacity results generated from the EPA-approved transmissometer against which the DOCS and EPA Reference Method 9-certified human observer opacity data were compared.

In evaluating the DOCS as a technically defensible alternative to EPA Reference Method 9, the mean opacity deviation (i.e., difference in opacity readings recorded by the DOCS and the EPA-certified transmissometer) for both black and white smoke plumes was computed and compared with the EPA Reference Method 9 statistical error rate of 7.5%.[3,5] Moreover, to ensure that technological decisions resulting from the field data could be supported with a known degree of confidence, the uncertainty associated with the opacity deviation measurement was quantified by computing both the 95 and 99% confidence intervals. Finally, conclusions regarding the equivalency of the DOCS to EPA Reference Method 9 were drawn from the application of statistical hypothesis testing on the smoke school field data.

RESULTS

The following section summarizes the statistical analysis of the DOCS field data collected at each of the three EPA-approved Reference Method 9 smoke schools. To provide technology decision-makers with a rational basis for drawing conclusions regarding the equivalency of the DOCS to EPA Reference Method 9, the field results were evaluated using a standard statistical hypothesis testing approach.

Ogden, UT, Smoke School

The Ogden, UT, smoke school field evaluation was conducted over a 3-day period from October 2 through October 4, 2001. The climatic conditions over the 3 days of the smoke school field trial are reported in Table 2. In general, the weather conditions during the Utah field tests

Table 2. Climatic parameters measured or reported during the DOCS field tests—Ogden.

	Day of Test		
	Day 1	Day 2	Day 3
Mean temperature (°F)	66.2	60.8	60.8
Average wind speed (mph)	8.9	9.7	8.1
Max wind speed (mph)	13.8	16.1	11.4
Wind direction[a]	N-NW	E-SE	S-SE
Sky conditions	Clear	Clear	Clear
Relative humidity (%)	27.2	45.2	30.5
Visibility (mi)	7	7	7
Barometric pressure (in. of Hg)	30.08	30.11	30.01
Precipitation (in)	0	0	0
Vertical sun angle (°)	42.2	39.4	38.5

[a]N-NW (north-by-northwest), E-SE (east-by-southeast), S-SE (south-by-southeast).

were ideal. The climatic conditions were characterized by (1) an average daily temperature range of 60–67 °F, (2) low humidity, and (3) light wind. Of greater importance in the measurement of visual opacity was the fact that sky conditions were clear, providing maximum color contrast between the plume and background.

Approximately 6400 opacity readings of visible emissions were taken as part of the DOCS field evaluation in Utah. Of that number, 4741 opacity readings (2336 black plumes and 2405 white plumes) or nearly 75% of those computed were deemed acceptable for the DOCS statistical analysis. The decision to exclude 2161 opacity readings from the DOCS statistical analyses was based on a number of technical problems including (1) physical obstruction of the smoke plume (e.g., trees, clouds, telephone poles), (2) folding, twisting, or other significant physical disruptions to the plume, and (3) inappropriate modification of digital image through use of the brush function that was available in the DOCS software package.[7]

Although there were a myriad of reasons for eliminating certain photographs from opacity analysis, the overwhelming majority of photographs that were deemed invalid during the Ogden field trial were eliminated because of the use of the DOCS brush function by the photograph readers. Because a consensus could not be reached among the research participants as to the level of bias that potentially could be introduced by the use of the brush function, a decision was made to exclude all opacity readings developed with the assistance of the brush function from the statistical analyses. As a result of the fact that this decision was made after collection of the DOCS readings, over 20% of the initial data set from the Ogden field tests had to be excluded from statistical analysis. For both the Georgia and Ohio smoke schools, the DOCS photograph readers were instructed not to use the brush function.

Quantitative Analysis. The three statistical parameters identified as critical in the technical evaluation of the DOCS were the (1) absolute value of the mean opacity deviation (e.g., opacity measurement recorded by DOCS minus the opacity measurement reported by the EPA-certified transmissometer), (2) 95% confidence interval of the mean opacity deviation, and (3) 99% confidence interval of the mean opacity deviation. Table 3 summarizes the value of these parameters calculated from the Ogden DOCS field tests.

It is important to note that, in addition to comparing the DOCS opacity measurements to the EPA-certified transmissometer readings, the mean deviation estimated from opacity readings recorded by EPA Reference Method 9-certified human observers also are included in Table 3 for comparison. The large difference in the number of readings recorded by the DOCS relative to the number reported by EPA Reference Method 9-certified human observers primarily was because of two aspects of the experimental design, including the fact that (1) one digital photograph could be evaluated by as many as eight DOCS photograph readers (i.e., maximum number of members on panel) while the certified human observer only provided one opacity reading per plume, and (2) certified

Table 3. Statistical data summary of Ogden smoke school DOCS evaluation.

Color of Smoke—Opacity Measurement Approach	Opacity Range	Mean Deviation (%)	Number of Samples	95% CI[a]	99% CI[b]
Black—DOCS	0–100%	6.4	2336	6.1–6.7	6–6.8
Black—certified observers	0–100%	6.7	246	5.7–7.8	5.4–8.1
Black—DOCS	0–60%	5.6	1957	5.3–5.9	5.2–6
Black—certified observers	0–60%	5.4	212	5.5–6.4	4.1–6.8
Black—DOCS	0–40%	5.4	1745	5–5.7	4.9–5.8
Black—certified observers	0–40%	4.8	194	3.8–5.7	3.5–6.1
White—DOCS	0–100%	10	2405	9.5–10.5	9.4–10.6
White—certified observers	0–100%	8.5	282	7.5–9.6	7.1–10
White—DOCS	0–60%	6.7	1897	6.3–7	6.2–7.2
White—certified observers	0–60%	8.2	224	7–9.4	6.6–9.8
White—DOCS	0–40%	5.9	1686	5.5–6.2	5.4–6.3
White—certified observers	0–40%	7.4	199	6.1–8.7	5.7–9

[a]95% CI—95% confidence interval; [b]99% CI—99% confidence interval.

human observers only provided visual readings during the first day of the 3-day field test.

Over the full range of opacity (i.e., 0–100%), the mean deviation recorded by the DOCS for black smoke was estimated to be 6.4% with 95 and 99% confidence intervals that ranged from 6.1 to 6.7% and 6 to 6.8%, respectively. These results demonstrated that, for black smoke, the DOCS exhibited an opacity error rate that was significantly less than the error rate associated with EPA Reference Method 9 (i.e., 7.5%).[3,5] Moreover, the range of the 99% confidence interval indicates that there is less than a 1% chance of the true mean deviation being greater than 6.8%. These statistical results support the conclusion that the accuracy of the DOCS to quantify the visible opacity of black smoke is equal to or greater than that established for the EPA Reference Method 9 procedure. Similarly, in evaluating the ability of certified smoke readers to measure the opacity of black smoke over the full opacity range, the mean deviation (e.g., certified human observer opacity reading minus the transmissometer opacity reading) was estimated to be 6.7%. Although the mean deviation was below the 7.5% error rate associated with the EPA Reference Method 9 procedure, the 95% confidence interval included deviations above 7.5%, a fact that suggests that there would be a high degree of uncertainty associated with the conclusion that the certified human readers could reliably maintain the EPA Reference Method 9 accuracy level.

In contrast to black smoke, the field data indicated that, over the full range of opacity (0–100%), neither the DOCS nor the certified human observers could achieve the EPA Reference Method 9 accuracy standard when measuring the opacity of white plumes. Both opacity measurement approaches yielded mean opacity deviations that were significantly greater than the error rate associated with EPA Reference Method 9 (i.e., 7.5%). The failure of the DOCS to accurately measure white plumes over the full range of opacity is suspected to stem from the inability of the DOCS computer software to exclude the effects of shadows, which are characteristic of high-opacity white plumes (i.e., those having opacities of greater than 60%).[7] Current investigations are being conducted to determine if modifications can be made to the DOCS computer software to effectively reduce the impact of shadows on visible opacity determinations.

With respect to human observers, it was interesting to note that not only did the certified readers fail to achieve the EPA Reference Method 9 opacity error rate during the measurement of white plumes, but the variability in their measurements (as reflected in both the 95 and 99% confidence intervals) was appreciably larger than that reported by the DOCS. In other words, for the weather conditions that prevailed at the Ogden field site, the DOCS results appear to be more consistent and reproducible than the opacity measurements reported by EPA Reference Method 9-certified human observers.

Despite the failure of the DOCS to meet the EPA Reference Method 9 opacity error rate requirement during the measurement over the full opacity range for white smoke plumes, when the statistical procedures were applied to a limited range of visible opacity, the DOCS not only met the accuracy requirement but was found to have a significantly greater accuracy than EPA Reference Method 9-certified human observers. For example, over the 0–60% opacity range for white smoke, the mean deviation of the DOCS was estimated to be 6.7% with 95 and 99% confidence intervals that ranged from 6.3 to 7% and 6.2 to 7.2%, respectively. These data demonstrate that, when measuring the opacity of white plumes having opacity levels equal to or less than 60%, the DOCS accuracy was significantly better than that of EPA Reference Method 9. Furthermore, the 99% confidence interval indicates that there is less than a 1% chance that the true mean deviation will be greater than 7.2. These statistical results support the conclusion that the accuracy of the DOCS in measuring the opacity of white smoke over the range of 0–60% opacity is significantly greater than that established for EPA Reference Method 9. In contrast to the ability of the DOCS to meet the EPA Reference Method 9 accuracy requirements when its application was limited to the 0–60% opacity range for white plumes, results from the certified human observers were significantly larger than that permitted by EPA Reference Method 9. For example, over the limited opacity range of 0–60%, the mean opacity deviation associated with EPA Reference Method 9-certified smoke readers was estimated to be 8.2% with a 95% confidence interval that ranged from 7 to 9.4%. Clearly, under the clear sky conditions encountered in Utah, the DOCS was determined to be a more accurate and precise opacity measurement method than were certified human observers.

Augusta, GA, Smoke School

The EPA-approved Georgia smoke school was conducted over 3 days from October 30 through November 1, 2001. The climatic conditions recorded during that time period are recorded in Table 4. The weather conditions during the smoke school field tests were characterized by mild temperatures, moderate winds, scattered clouds, and partly overcast skies.

Not only were the weather conditions in Augusta, GA, found to be appreciably different from those encountered in Ogden, but the physical landscape of the two smoke school locations were drastically different as well. For example, while the Ogden smoke school field

Table 4. Climatic parameters measured or reported during the DOCS field tests—Augusta.

	Day of Test		
	Day 1	Day 2	Day 3
Mean temperature (°F)	63.1	60	67.5
Average wind speed (mph)	4	5.3	5
Max wind speed (mph)	4.6	11.5	9.2
Wind direction	N	N	S-SE
Sky conditions	Partly cloudy	Scattered clouds	Cloudy
Relative humidity (%)	50.9	72	90.9
Visibility (mi)	10	10	7.9
Barometric pressure (in. of Hg)	30.36	30.42	30.27
Precipitation (in)	0	0	0
Vertical sun angle (°)	32.4	31	28.6

tests were conducted in a large open parking lot located adjacent to a university athletic stadium, the venue for the Georgia smoke school was a much smaller and secluded parking lot surrounded by a dense pine forest. The combination of cloudy conditions and tall trees in the vicinity of the smoke generator provided a more variable background against which the DOCS and EPA Reference Method 9-certified human observers were expected to estimate plume opacity.

Quantitative Analysis. Unlike in the Utah smoke school field test, in the analysis of the Georgia smoke school data, use of the DOCS brush function was not permitted in the analysis of any digital photographs. Furthermore, with several of the DOCS camera operators certified as EPA Reference Method 9 visual observers, a larger number of EPA Reference Method 9-certified readers were available to participate in the side-by-side opacity method comparison during the first day of smoke school. Table 5 provides a summary of the DOCS statistical data generated from the Augusta smoke school field tests.

Over the full range of opacity for black smoke, neither the DOCS nor the EPA Reference Method 9-certified human observers were able to achieve the opacity error rate established by EPA Reference Method 9. The mean opacity deviation recorded by the DOCS for black smoke was 8.6%, while certified readers recorded a mean opacity deviation of 8.4%.

Despite the inability of the DOCS to achieve the accuracy requirements specified for supporting method equivalency during the Georgia field tests, the variability in the DOCS analyses was much less than that estimated for certified smoke readers. The 95% confidence interval about the mean deviation for the DOCS was estimated to be 8.4–8.9% while that for EPA Reference Method 9 certified human observers ranged from 6.2 to 10.6%. These data demonstrate that the DOCS technology is more precise and reproducible than human observers. However, over the limited opacity range of 0–60% for black smoke, certified readers appeared to be more accurate than the DOCS with a reported mean opacity deviation of 6.1% compared with 8.2% estimated for the DOCS. The reasons for the improved accuracy of certified smoke readers to quantify opacity under the limited opacity range was unclear. The likely possibility is that the Method 9-certified human observers utilized a background other than sky to improve the level of color contrast exhibited by the plume (e.g., trees, telephone poles, billboard signs).

Although the use of objects other than sky in estimating plume opacity at a smoke school setting is permissible, the practice does not reflect the environment in which Method 9-certified readers would actually apply the method in practice. The smoke school stack in an EPA-approved smoke school field test is ~15 ft above ground level. At this height, objects such as trees, telephone poles, billboard signs, and so on are normally within the line of site such that they can be employed by a human observer to improve visual contrast, giving the human observer an enhanced ability of "passing" smoke school. On the other hand, under normal circumstances in which a Method 9 evaluation in the field would be conducted, the visual observer typically

Table 5. Statistical data summary of Augusta smoke school DOCS evaluation.

Color of Smoke—Opacity Measurement Approach	Opacity Range	Mean Deviation (%)	Number of Samples	95% CI[a]	99% CI[b]
Black—DOCS	0–100%	8.6	4949	8.4–8.9	8.3–9
Black—certified observers	0–100%	8.4	543	6.2–10.6	5.5–11.3
Black—DOCS	0–60%	8.2	3620	7.9–8.5	7.8–8.6
Black—certified observers	0–60%	6.1	398	5.4–6.9	5.2–7.1
Black—DOCS	0–40%	7.9	2896	7.5–8.2	7.4–8.3
Black—certified observers	0–40%	4.7	315	4.1–5.4	3.8–5.6
White—DOCS	0–100%	13.2	3535	12.6–13.8	12.5–13.9
White—certified observers	0–100%	6.2	365	5.4–6.9	5.2–7.2
White—DOCS	0–60%	8.5	2565	8.1–8.9	8–9.1
White—certified observers	0–60%	4.9	265	4.3–5.6	4–5.8
White—DOCS	0–40%	7.2	2203	6.8–7.6	6.6–7.7
White—certified observers	0–40%	4.1	227	3.6–4.7	3.4–4.9

[a]CI—95% confidence interval; [b]CI—99% confidence interval.

is measuring the plume opacity generated by a stack located on top of a building or a stack that may be hundreds of feet in height.

With respect to its ability to measure the opacity of white plumes, the DOCS was capable of achieving the EPA Reference Method 9 error rate only when the opacity range was limited to between 0 and 40%. Conversely, the EPA Reference Method 9-certified human observers were able to meet the EPA Reference Method 9 error rate over the full range of opacity when analyzing white smoke plumes. Again, although it is not entirely clear why Method 9-certified human observers were able to perform significantly better than the DOCS when reading white smoke plumes during the Augusta, GA, smoke school, it is highly probable that with the large number of tall trees and other vegetation surrounding the Georgia smoke school venue, the Method 9-certified human observers were able to strategically position themselves to view the white plumes using the dark foliage, which essentially provided a more effective contrasting background than the use of sky for viewing white smoke plumes. However, even with less color contrast available to evaluate opacity, the DOCS was able to achieve the Method 9 opacity error rate over the opacity range of regulatory interest (i.e., 0–40%).

Columbus, OH, Smoke School

The EPA-approved Ohio smoke school was conducted over 3 days from March 26 through March 28, 2002. The climatic conditions recorded during that time period are recorded in Table 6. The venue for the Columbus, OH, smoke school was a vehicular parking lot located in one of the city's municipal parks. Weather conditions during the Ohio field tests were considerably different from those during either the Utah or Georgia smoke schools. The climate in Columbus for the field tests was characterized by freezing temperatures, light rain mixed with snow, and thick, overcast skies.

Table 6. Climatic parameters measured or reported during the DOCS field tests—Columbus, March 26–March 28, 2002.

	Day of Test		
	Day 1	Day 2	Day 3
Mean temperature (°F)	32	33	37
Average wind speed (mph)	7.8	6.9	5.1
Max wind speed (mph)	13.8	11.5	13.8
Wind direction	NW	NW	S
Sky conditions	Freezing rain, overcast	Haze, overcast	Overcast, scattered clouds
Relative humidity (%)	93	83.2	95
Visibility (mi)	5.5	8.5	5.7
Barometric pressure (in. of Hg)	29.98	30.18	30.15
Precipitation (in.)	0.77	0	0
Vertical sun angle (°)	No sun	38	46

Quantitative Analysis. Like the Augusta smoke school, in the analysis of the Columbus smoke school DOCS data, the DOCS brush function was not used to evaluate any of the digital photographs. Furthermore, because all of the DOCS camera operators also were certified as EPA Reference Method 9 human observers, a larger number of EPA Reference Method 9-certified human observers were available to participate in the side-by-side opacity method comparison conducted during the first day of smoke school. A summary of the DOCS statistical data obtained from the Columbus smoke school is presented in Table 7.

Over the full range of opacity for both black and white smoke, neither the DOCS nor the EPA Reference Method 9-certified human observers were able to achieve the error rate established by EPA Reference Method 9. The mean opacity deviation recorded by the DOCS for black smoke was 10.9%, while EPA Reference Method 9-certified readers recorded a mean opacity deviation of 12%. Similarly, for white smoke, the mean opacity deviation recorded by the DOCS was 21.6%, while EPA Reference Method 9-certified human observers recorded a mean opacity deviation of 10%.

The failure of both the DOCS and EPA Reference Method 9-certified human observers to achieve the EPA Reference Method 9 opacity error rate was unexpected but not surprising given the challenging weather conditions. In other words, when climatic conditions are unfavorable for Method 9-certified human observers to measure opacity, the DOCS also experiences difficulty. A common concern expressed by many of the smoke school participants was their inability to actually visualize the plume using the sky as background. Technical guidance provided by the EPA-approved smoke school contractors states that when faced with a situation where there is choice of backgrounds, the human observer should always choose the one that provides the greatest contrast because it will permit the most accurate opacity reading.[5] Neither the technical guidance nor the EPA Reference Method 9 specifies sky as the only suitable background that can be used to quantify opacity. However, by utilizing a smoke generator with a 15-ft stack height, establishing a more suitable background than sky is more likely in a real-world application of Method 9 in which the stack can be more than several hundred feet in height. Under these latter conditions, opacity must be read against a sky background.

Another concern raised by smoke school participants was their inability to visually identify the position of the sun relative to the smoke stack. EPA Reference Method 9 requires that the sun be at the back of the observer when

Table 7. Statistical data summary of state of Ohio smoke school DOCS evaluation.

Color of Smoke—Opacity Measurement Approach	Opacity Range	Mean Deviation (%)	Number of Samples	95% CI[a]	99% CI[b]
Black—DOCS	0–100%	10.9	3498	10.6–11.3	10.4–11.5
Black—certified observers	0–100%	12	1492	11.4–12.5	11.3–12.7
Black—DOCS	0–60%	9.4	3066	9.0–9.7	8.9–9.8
Black—certified observers	0–60%	10.6	1192	10–11.1	9.9–11.3
Black—DOCS	0–40%	8.1	2753	7.7–8.4	7.6–8.5
Black—certified observers	0–40%	9.2	1012	8.7–9.8	8.5–9.9
White—DOCS	0–100%	21.6	4394	21–22.2	20.8–22.4
White—certified observers	0–100%	10	1500	9.5–10.5	9.4–10.6
White—DOCS	0–60%	15	3758	14.6–15.4	14.4–15.5
White—certified observers	0–60%	9.7	1176	9.2–10.3	9.1–10.4
White—DOCS	0–40%	12.3	3131	12–12.6	11.9–12.7
White—certified observers	0–40%	9.5	1020	9–10.1	8.8–10.3

[a]CI—95% confidence interval; [b]CI—99% confidence interval.

quantifying plume opacity. Although there are various methods to determine the exact position of the sun during cloudy or overcast days given an individual's position (i.e., latitude, longitude), time of year, and time of day, no efforts beyond visual observations were made to determine sun location during DOCS field evaluation.[10] Therefore, field personnel could not verify compliance with this aspect of the method.

Finally, although EPA Reference Method 9 does not specify when visual opacity measurements should not be taken, under climatic conditions that result in a less contrasting background, the apparent plume opacity can approach 0.[5] As a result, significant negative bias (error) can occur when an attempt is made to measure plume opacity under severely cloudy or overcast sky conditions. Finally, under dark overcast sky conditions or any climatic conditions in which visual contrast between the plume and sky can not be readily established, it is more likely that a visual opacity determination should not be made regardless of the method employed.

Hypothesis Testing

Although a defensible evaluation of the equivalency of any alternative method to EPA Reference Method 9 can be achieved by comparing the mean opacity deviation and its confidence interval to the established EPA Reference Method 9 error rate, environmental regulators have expressed their preference for the application of a more formalized significance test when addressing method equivalency.[6,11] In significance testing, a null hypothesis (H_o) is developed that will be assumed to be true in the absence of strong quantitative evidence to the contrary. The H_o for the present study may be stated as follows: "*The true mean difference between the transmissometer and the DOCS opacity measurements is greater than 7.5%.*" This statement reflects the assumption that, in the absence of strong quantitative data to the contrary, the two opacity measurement methods will be assumed to be different. Similarly, the alternative hypothesis (H_a) may be constructed as follows: "*The true mean difference between the transmissometer and the DOCS opacity measurements is equal to or less than 7.5%.*" The rationale for constructing the null and alternative hypotheses in this fashion is to shift the burden of proof for demonstrating EPA Reference Method 9 equivalency to the strength of the DOCS field data. In other words, in the absence of field data that strongly support the rejection of the null hypothesis, the conclusion drawn from the data will be that the DOCS is not equivalent to EPA Reference Method 9. Alternatively, if the strength of the data were sufficient to reject the H_o (acceptance of H_a), the conclusion drawn from this study will be that the DOCS is statistically equivalent to EPA Reference Method 9. The null and alternative hypotheses may be presented mathematically as illustrated by eqs 1 and 2, respectively. (Note: δ_o is the true mean difference between the DOCS and actual plume opacity as measured by the EPA-certified transmissometer.)

$$\text{Null Hypothesis } (H_o)\text{: } \delta_o > 7.5 \tag{1}$$

$$\text{Alternative Hypothesis } (H_a)\text{: } \delta_o \leq 7.5 \tag{2}$$

Given a desired level of significance, α, and degrees of freedom ($n - 1$), eqs 3 and 4 define the critical t value and test-statistic (t_{test}), respectively. The values of these two parameters are compared with one another to determine whether the strength of the data is sufficient to reject the null hypothesis (Table 8).

$$\text{Critical } t\text{-value: } t_{crit} t_{(\alpha/2),n-1} \tag{3}$$

$$\text{Test statistic: } t_{test} \frac{\bar{d} - \delta_o}{\frac{s_d}{\sqrt{n}}} \tag{4}$$

where n is number of paired measurements (i.e., DOCS and transmissometer); d is mean difference between the DOCS and transmissometer measurements; $s_d/\sqrt{n}$ is standard error; and s_d is square root of variance.

Table 8. Test conditions used for evaluating the statistical equivalency of the DOCS to EPA Reference Method 9.

(a) Test Condition: If $t_{test} \leq t_{crit}$, then the null hypothesis, H_o, is rejected (accept H_a – DOCS is statistically equivalent to EPA Reference Method 9).
(b) Test Condition: If $t_{test} > t_{crit}$, the data do not support rejection of H_o (accept H_o – DOCS is not statistically equivalent to EPA Reference Method 9).

In practical terms, rejection of the null hypothesis is tantamount to accepting the DOCS as an equivalent method to EPA Reference Method 9, while failure to reject the null hypothesis essentially means that the DOCS is not a statistically equivalent method. Table 9 summarizes the results of hypothesis testing using data obtained from the three EPA-approved smoke schools.

Information drawn from hypothesis testing yielded mixed results with respect to the equivalency of the DOCS to EPA Reference Method 9. In all but one opacity range (white plumes with true opacity levels in excess of 60%), the data from the Utah smoke school supported rejection of the null hypothesis, indicating that the conclusion drawn from that data set should be that the DOCS is statistically equivalent to EPA Reference Method 9. Conversely, in the Georgia and Ohio smoke schools, the DOCS field data, in general, failed to support the rejection of the null hypothesis. However, drawing the conclusion that the DOCS is not equivalent to EPA Reference Method 9 under cloudy or overcast sky conditions may not be defensible given the fact that the DOCS is limited to utilizing sky as background and, under conditions encountered at EPA-approved Method 9 smoke schools, certified human observers are not.

The ability of the DOCS to accurately estimate plume opacity is dependent on the visual contrast provided by sky conditions. However, under the smoke school scenario, certified human observers are less dependent on sky conditions because the smoke generators employed at EPA-approved smoke schools have relatively low stack heights that afford human observers the possibility of selecting any background with which to estimate opacity.

DISCUSSION

Data from the DOCS field study indicated that digital imagining technologies have the potential to accurately and reliably measure the opacity of smoke plumes when weather conditions provide optimum color contrast between plume and background. Under clear blue sky conditions, the DOCS was able to consistently meet the EPA Reference Method 9 performance standard and, over opacity ranges of regulatory importance (i.e., 0–40% opacity), the DOCS accuracy was significantly better than that achieved by EPA Reference Method 9-certified human observers.

Table 9. Summary of hypothesis testing performed at the 0.05 significance level.

Smoke School	Color of Smoke	Opacity Range (%)	Mean[a] Deviation (%)	No. of Samples (*n*)	Significance Level (α)	Critical[b] T Value	Test Statistic	Rejection[c] of Null Hypothesis?
UT	Black	0–100	6.4	2336	0.05	1.96	−6.77	Yes
	Black	0–60	5.6	1957	0.05	1.96	−12.08	Yes
	Black	0–40	5.4	1745	0.05	1.96	−12.5	Yes
	White	0–100	10	2405	0.05	1.96	10.39	No
	White	0–60	6.7	1897	0.05	1.96	−4.35	Yes
	White	0–40	5.9	1686	0.05	1.96	−8.99	Yes
GA	Black	0–100	8.6	4949	0.05	1.96	8.06	No
	Black	0–60	8.2	3620	0.05	1.96	4.49	No
	Black	0–40	7.9	2896	0.05	1.96	2.22	No
	White	0–100	13.2	3535	0.05	1.96	19.93	No
	White	0–60	8.5	2565	0.05	1.96	4.72	No
	White	0–40	7.2	2203	0.05	1.96	−1.47	Yes
OH	Black	0–100	10.9	3498	0.05	1.96	16.83	No
	Black	0–60	9.4	3066	0.05	1.96	10.24	No
	Black	0–40	8.1	2753	0.05	1.96	3.53	No
	White	0–100	21.6	4394	0.05	1.96	46.81	No
	White	0–60	15	3758	0.05	1.96	36.32	No
	White	0–40	12.3	3131	0.05	1.96	28.67	No

[a]Employment of the brush function by the DOCS users was not permitted during digital photograph analysis; [b]From standard statistical tables, for $\alpha = 0.05$ and $n > 120$, t critical is ~1.96; [c]Where the null hypothesis is rejected, the data indicate that DOCS is equivalent to EPA Reference Method 9. Conversely, if the null hypothesis is not rejected, the conclusion is that DOCS is not equivalent to EPA Reference Method 9.

The decision not to employ the DOCS brush function during the field trials may have limited unfairly the digital technology from demonstrating its full performance capability. Conceivably, a DOCS technology user employing the brush function would have had the opportunity to cut and paste a darker background with which to evaluate white smoke plumes and a lighter background to evaluate the opacity of black smoke plumes. By improving the contrast between the plume emissions and background, a more accurate opacity reading can be made. Moreover, using the digital technology allows an interested party the ability to reevaluate how the plume background was established after the initial opacity measurement has been reported. It is anticipated that once the technical implications of utilizing the brush function have been fully explored and documented, a future opacity assessment of the smoke school digital photographs using the brush function may be warranted.

CONCLUSIONS

The results for the three smoke school field tests suggest that climatic conditions have a profound effect on the ability of the DOCS and Method 9-certified smoke readers to meet the performance criteria established by EPA Reference Method 9. During the Utah field test, sky conditions were clear, which provided optimal color contrast between plume and sky. Under these conditions, the DOCS error rate was significantly less than that established under EPA Reference Method 9. Moreover, the DOCS opacity readings were consistently more accurate than those recorded by Method 9-certified human observers. Alternatively, when smoke plumes were viewed under weather conditions characterized by cloudy or overcast skies, the DOCS and Method 9-certified human observers had difficulty in accurately quantifying opacity. This reduced ability to measure opacity was not surprising given the fact that, as color contrast between the plume and sky conditions diminishes, apparent opacity also decreases. When the DOCS and human observers are compelled to use sky as background, the accuracy of the DOCS in quantifying plume opacity clearly surpasses that of Method 9-certified observers. However, under conditions encountered at EPA-approved smoke schools, human observers can often take advantage of the relatively low stack height of smoke generators to employ objects other than sky (e.g., trees, light poles) with which to quantify opacity. This ability represents a clear advantage for human observers in their attempt to pass smoke school but does not reflect the typical Method 9 field application under which plume opacity from stacks with heights much greater than the local tree line can be estimated. Under these conditions, the sky must be used as a visual background.

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